The value of size

Bioeconomic consequences of size-dependent pricing and fishing-induced evolution

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SCIENTIFIC ENVIRONMENT

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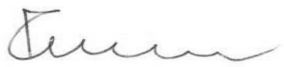
Bergen, June 2011



Fabian Zimmermann

It was the Law of the Sea, they said. Civilization ends at the waterline.
Beyond that, we all enter the food chain, and not always right at the top.
Hunter S. Thompson

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ABSTRACT

The influence of fishing on the dynamics of fish stocks is a core element in fisheries management. One of the most notable characteristics in this context is the size-structure of a fish stock, composed by the individual and its body size. From a biological perspective, individual size is directly linked to most relevant life-history traits like growth, maturation or reproductive output, connecting it to evolutionary processes. In the context of fisheries, individual fish constitute the harvested biomass and therefore its overall value. In addition, individual size possesses an intrinsic economic value: Commonly, bigger fish are more valuable than smaller ones and fetch higher prices per weight unit. Thus, size-dependent pricing underlines in economic terms the relevance of individual size, and suggests at the same time an interaction with demographic shifts through fishing. Generally, policies accounting for individual growth and size structure can improve yield and economic returns, therefore an interactive influence of size-dependent pricing on optimal harvest strategies is likely. Similarly, to take into account the impact of potential evolutionary changes in stock composition through fishing could improve the long-term economic benefits from fisheries.

In paper I and II, the influence of size-dependent pricing on optimal harvest strategies is evaluated. Positive relationships between individual sizes of fish and the prices per weight unit fishermen receive are widespread in commercial fisheries. This underlying hypothesis is evaluated in **Paper III** with a statistical analysis of price data from Norwegian fisheries. Furthermore it is commonly assumed that such size-dependent pricing can influence the optimal catch composition maximizing economic rent. This raises the question whether the impact on optimal harvest strategies and corresponding maximum economic yield is of significant magnitude, and hence should be considered in management decisions. **Paper I** addresses this issue with age-structured models parameterized for two pelagic fisheries in Norway, targeting Atlantic herring (*Clupea harengus*) and Atlantic mackerel (*Scomber scombrus*). Here positive size-dependent pricing results in lower optimal harvest, higher average catch size and influences net

present value. On the other hand, **paper II** provides an analytical approach, introducing size effects into a generic Gordon-Schaefer type model. The assumption of a negative relationship between fishing effort and average individual size emulates a fishing-induced truncation of size structure, while mean catch size is positively related to price to account for size-dependent pricing. This allows for tracing how such size-dependent effects change the patterns of optimal harvest paths and sustainable revenue in fish stocks. The results show a decrease of optimal effort and harvest with increasing strength of size effects. Therefore, **Paper I** and **II** suggest that ignoring the impact of fishing on size structure of fish stocks as well as size-dependent pricing could result in suboptimal management strategies and rent dissipation. **Paper III** underlines this conclusion and demonstrates that size-dependent pricing is indeed relevant in Norwegian fisheries.

In **Paper IV**, a simplified evolutionary life-history model was utilized to explore potential economic consequences of fishing-induced evolutionary changes. The underlying assumption is based on evidences that harvesting of fish stocks changes survival probabilities and therefore selection landscape for life-history strategies, resulting in adaptations of corresponding traits like maturation age. Hence, the model focuses on age at maturation as basis of stock dynamics for a cod-like species, while fishing is described by fishing mortality and size selectivity. Combined, these parameters determine the resulting yield and net revenue of the simulated fishery. A comparison of this model with a non-evolutionary version allows for an impact analysis of harvest strategies on life history evolution and the long-run economic consequences. The results predict an influence of fishing-induced evolution on stock biomass and composition as well as yield and economic rent. However, the quantitative impact is marginal even under low discount rates and the consequences for optimal harvest patterns moderate. Negative economic consequences are present for stocks managed within the range of maximum economic yield, while evolutionary adaptation provides beneficial resilience towards high fishing pressure. Nevertheless, under consideration of fishing-induced evolution fishing mortalities maximizing economic rent remain nearly the same for most parameter values, implying that optimal harvest strategies are not significantly affected by an evolutionary component. Additionally, the results show high sensitivity to discounting: Increasing discount rates render the influence of fishing-induced evolution irrelevant even on the level of low to moderate discount rates. This highlights the problematic effect of discount rates in long-term cost-benefit calculations, and calls for a careful use of discounting in view of small but detrimental changes over long time periods.

THE ECONOMICS OF FISHING

"It will appear, I hope, that most of the problems associated with the words "conservation" or "depletion" or "overexploitation" in the fisheries are, in reality, manifestations of the fact, that the natural resources of the sea yield no economic rent."

H. Scott Gordon, 1954

FISH – A NATURAL RESOURCE

Aquatic organisms are one of the world's pivotal renewable resources, providing food, employment and other benefits on a global scale. Most prominent are commercial fisheries and aquaculture with a total production volume of 145.1 million tones in 2009 (FAO 2011), whereof marine fisheries contribute the main part (55%) with a stable production. Aquaculture has become increasingly important, now accounting for 38% of the total volume, while inland fisheries remain a minor factor (7%). Fisheries and aquaculture provide direct or indirect livelihoods for estimated 540 million people, and human consumption represents the primary utilization (81%), resulting in all-time high of 17.2 kg per capita annual fish supply in 2009. Correspondingly, fish contributed 15.7% to the global population's intake of animal protein in 2007 (FAO 2011).

Fish is a particularly important food source in developing countries, therefore a key component for future food security in view of population growth and environmental threats (Kent 1997, Garcia and Rosenberg 2010). However, the progression from artisanal to industrial fishing resulted in four-fold increase of total catch over the second half of last century, threatening fish as a future resource (Pauly et al. 2002). Today, unsustainable exploitation and habitat degradation peril global fish stocks, and therefore the natural capital and food source they represent (Pauly et al. 2005, Godfray et al. 2010).

In summary, there is substantial wealth generated globally in connection with fish and fisheries. At the same time, mismanagement and detrimental utilization put the continuity of those resources at risk and squander potential benefits on massive scale

(World Bank 2009). The study of these systems at the intercept point between biology and economics is therefore not only of scientific value but embodies high socioeconomic relevance. The disciplines of bioeconomics and fisheries management may provide here important answers for the problems and challenges to achieve sustainability and efficiency.

EVOLUTION OF FISHERIES ECONOMICS

From today's perspective, the sweeping absence of scientific and political debate until mid 20th century on the utilization and management of fish stocks may be puzzling. However, it illustrates impressively how the way society bears upon the environment and natural resources has changed, as well as the scientific progress that has been made in the past decades. The levity of previous generations in this matter becomes more understandable in view of a vast resource and limited technological possibilities of past fishermen. Hence, the fallacy that fishing cannot cause a significant impact on fish stocks was common even among biologists. A drastic change in the situation began with large-scale industrial fisheries after World War II, accentuating the need for a paradigm shift.

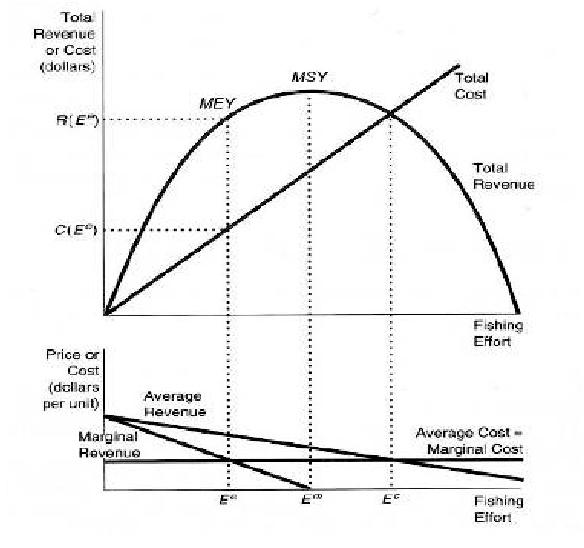
The technological development of fisheries found its echo in several corner stones of modern fisheries management published in the same period (Gordon 1954, Schaefer 1954, Scott 1955, Beverton and Holt 1957). Conceptually, the ideas may be divided into a biological approach contrasting the economic perspective: R. Beverton and S. Holt, as well as M.B. Schaefer focused on dynamics of exploited stocks while A. Scott's book contained a "then confusing notion of conservation of natural resources in terms of stewardship of assets" (Wilen 2000). Gordon on the other hand discussed the problem of overexploitation in an open-access resource and thus portended what later became more generally known as the "tragedy of the commons" (Hardin 1968). Particularly the work of Gordon and Schaefer offered with their perceptive simplicity an essential understanding of key mechanisms in a fishery – and still do. This is easily underlined by the fact that the Gordon-Schaefer model remains until today the pedagogical tool of choice to explain characteristics of a common-property resource (Tietenberg and Lewis 2008).

The main achievements of the Gordon-Schaefer model are the concepts of maximum sustainable yield (MSY), maximum economic yield (MEY) and open-access equilibrium. MSY describes the stock size and corresponding fishing effort where yield is highest, i.e. a simple maximization of biological productivity. MEY on the other hand incorporates economics as part of the fishery, defining the yield where economic rent is maximized. This is contrasted by the open-access equilibrium, characterized by zero economic returns from additional harvest and therefore full rent dissipation (Gordon 1954, Gardner et al. 1990).

Yet, the static framework's disregard for the temporal component of resource exploitation was cause for some concern, as already Scott had recognized (Scott 1955).

THE GORDON-SCHAEFER MODEL

The Gordon-Schaefer model (Schaefer 1954, Tietenberg and Lewis 2008) combines a logistic growth model with simple economic assumptions to an equilibrium model of a fishery, describing stock productivity and corresponding fishing effort under assumption of constant price and constant marginal cost. Under effort E^m biological yield is maximized, while with E^e the efficient allocation of effort is achieved (marginal cost = marginal revenue) and economic rent highest. Without regulation effort is increased until rent is fully dissipated, i.e. total cost equals total revenue, defining the open access situation. Limitations are the simplified stock dynamics, ignoring ecosystem interactions, demographics and genetics, as well as fleet dynamics.



Therefore, fisheries economics progressed significantly with the introduction of dynamic solutions to the problem of optimal resource utilization and an elaborated capital theory. The first model accounting for dynamics dates back to Crutchfield and Zellner (1962), concluding, however, little influence on the outcome. This dissented Scott's notion that high discount rates could shift MEY towards the effort level of an open-access situation. Consequently, dynamic solutions to fisheries problems were considered to be of little relevance (Turvey 1964), even by Scott himself (Christy and Scott 1965). Optimal control-theory (Pontryagin et al. 1962) provided here a new powerful tool, but its implementation into resource economics towards the end of the decade was viewed as mere complication (Munro 1992). It was mainly C.W. Clark who caused a paradigm shift as he demonstrated the impact of dynamic solutions: Effort yielding MEY can surpass MSY-effort (Clark 1971) and the difference between discount rate and intrinsic growth rate can affect optimal harvest strategies (Clark 1973). Based on this, Clark highlighted the peculiarity of fish stocks as natural capital (Clark and Munro 1975). Collecting those threads, "Mathematical bioeconomics" (Clark 1976) proved itself as a seminal work that provided strong argument for the interdisciplinarity of fisheries science. In spite of the more recent scientific and political advancements (Wilen 2000, Bjørndal et al. 2007, Clark 2010), the basic principles and questions remained rather perpetual. Foremost the quest for MEY is still the dominating thread for fisheries economists (Grafton et al. 2007, Dichmont et al. 2010).

CURRENT STATUS AND MANAGEMENT PERSPECTIVE

The conclusive and aging theoretic directives to optimal resource utilization are contrasted by prevalent management failure in reality as well as a poor state of the world's fisheries and marine resources today (Jackson 2008, Holt 2009, World Bank 2009, FAO 2011). Renowned fisheries scientists draw a bleak picture, attesting a trophic down-fishing (Pauly et al. 1998), "worldwide crisis in fisheries" (Clark 2006a), the collapse of all fisheries in near future (Worm et al. 2006) and ultimately the "end of fish" (Pauly 2009). These assessment are not unchallenged (Murawski et al. 2007, Branch

INDIVIDUAL TRANSFERABLE QUOTAS

Individual transferable quotas are one type of dedicated access rights, distributing total allowable catches (TAC) as quota shares to private individuals (Squires et al. 1995, Grafton 1996, Branch et al. 2006). The quota share is fully transferable and can therefore be traded. First described by F.T. Christy (1973), ITQs remained a theoretical concept for almost two decades until first implementations in Icelandic and New Zealand fisheries (Sissenwine and Mace 1992, Annala 1996, Arnason 1996). Since then they gained increasing acceptance as a management tool. The key advantage of ITQs is their transferability: More efficient fishermen can buy quota shares from less efficient fishermen. This results in a overall increase of economic efficiency in the fishery. Additionally, future rents promote stewardship for the fish stock among the quota owners. But there is a downside to both points: Quota trading can lead to monopolization, and potentially huge increases in values raise questions of social equity (Clark 2006a). In particular, critics point out that free endowment of fishermen and lack of temporal restrictions can lead to substantial private profits from a public good (Macinko and Bromley 2003). ITQs also do not guarantee biological sustainability, but generate solely economic efficiency. Therefore successful ITQ management still relies on an adequate TAC and strict enforcement of quota and gear restrictions.

2008, Daan et al. 2011, Hilborn 2011), and recent studies come to more complex conclusions (Dankel et al. 2008, Mora et al. 2009, Worm et al. 2009). In particular, there are widespread counterexamples of successful management (Beddington et al. 2007, Hilborn 2007a, c, Costello et al. 2008). Furthermore, flawed conclusion based on unclear objectives (Hilborn 2007d), arbitrary reference points (Hilborn and Stokes 2010) or inconclusive catch data (De Mutsert et al. 2008, Branch et al. 2010) require consideration. Nonetheless, the overall performance of global fisheries is mediocre at best, raising the question: What went wrong?

The reasons for overfishing, unsustainable practices and economic underperformance are diverse and rarely straight-forward. From an economic perspective, the problems in fisheries originate in market failures connected to deficient property rights, quota system designs, user conflicts or insufficient enforcement (Clark 2006b, Grafton et al. 2008). Thus, a common symptom of fisheries mismanagement is overcapitalization, often caused by subsidies (Munro and Sumaila 2001, Clark et al. 2005, Sumaila et al. 2008, Sumaila et al. 2010). This problem is strongly linked to unsustainable total allowable catches (TACs) due to political decisions instead of scientific advice (Pauly, et al. 2002). Catch restrictions are further undermined by illegal, unreported and unregulated (IUU) fishing activities, particularly in absence of an adequate legal framework or sufficient enforcement (Gallic and Cox 2006, Sumaila et al. 2006, Agnew et al. 2009)

A key role in overfishing and rent dissipation can be attributed to improper access, property and use rights (Schlager and Ostrom 1992, Scott 2008). Hence, fishermen behaviour and fleet dynamics are a crucial factor (Branch, et al. 2006). However, previous quota systems often provided improper incentives and therefore failed in reality (Hilborn et al. 2005, Clark 2006a): A race-to-fish, high-grading and discarding as some of the most notable unwanted effects of unsound quota system designs (Pascoe 1997, Sutinen 1999, Hilborn 2007b). A potential cause is the prevalent management focus on biological reference points and the health of fish stocks, disregarding economic objectives as driving force of fisheries (Wilen 2000, Hilborn 2002, Branch, et al. 2006). Yet economic factors are from society's viewpoint a key purpose of fisheries and demand adequate attention in fisheries management. In this context, catch shares in form of individual fishing quotas (IFQs) or individual transferable quotas (ITQs) gain increasing acceptance as potential remedy (Squires, et al. 1995, Grafton 1996, Grafton et al. 2006). Signs of success substantiate this notion (Chu 2009, Costello et al. 2010), although a cautious implementation is required (Bromley 2009, Grafton et al. 2009, Gibbs 2010, Sumaila 2010), and the appropriate choice of management instruments depend on specific situations and challenges (Kompas et al. 2008, Hannesson 2011).

ALTERNATIVE USES AND ECOSYSTEM BENEFITS

The direct benefits from commercial fisheries are supplemented by alternative use values and non-use values of fish, frequently leading to stakeholder conflicts over the resources. Particularly recreational fishing generates substantial benefits (Connelly and Brown 1991, Pitcher and Hollingworth 2002), but may also contribute to stock depletion (Post et al. 2002, Coleman et al. 2004, Cooke and Cowx 2004) and is commonly understudied. Furthermore, recreational fishing is connected to benefits through tourism, and therefore relates to non-consumptive use values of aquatic systems and the ecosystem services they provide (Costanza 1997).

Ecological economics define ecosystem services as a flow of energy, information and material from natural capital within ecosystems to the benefit of human welfare (Costanza 1997, Millennium Ecosystem Assessment 2005). This includes direct and indirect use and non-use values, ranging from food production and recreational purposes to climate regulation, pollution control or sediment retention. Commonly markets captures these services only partially or not all, and quantitative valuation is often difficult. In fisheries management some ecosystem approaches attempt to account for additional ecosystem services, but globally most policies focus solely on (single) fish stocks as food source. Here integration of ecological economics and alternative stakeholder interests could result in improved sustainability and alignment of objectives as part of a “new consensus” (Hilborn 2007).

THE BIOLOGY BEHIND ECONOMICS

"I think the major opposition to ecology has deeper roots than mere economics; ecology threatens widely held values so fundamental that they must be called religious"

Garrett Hardin, 1982

FISH STOCKS AS BIOLOGICAL SYSTEMS

As fisheries biologists tend to underestimate the economic complexity of a fishery, so are fish rarely grasped as the biological entities they are in fisheries economics. Fish stocks are subpopulations of a fish species, and therefore subject to population dynamics and demographics. Furthermore, a fish stock exists in an ecological and evolutionary context, including all biological interactions in the framework of an ecosystem, as well as the underlying environmental determinants. The resulting inherent complexity of a fish stock elevates it above more trivial resources. Consequently, harvesting fish involves much more than a mere removal of biomass as economic models traditionally suggest. Thus, simplifications of low-dimensional lumped-biomass models could be a reason for unsatisfactory management results (Krysiak and Krysiak 2002, Tahvonen 2008).

IMPACT OF FISHING

Fishing imposes additional mortality on a fish stock, commonly enhanced by size selectivity, and alters the demographic composition of the stock. Truncations of size structure may impair the recruitment potential of fish stocks (Murawski et al. 2001, Berkeley et al. 2004b), destabilize population dynamics (Anderson et al. 2008) and increase population variability (Longhurst 2002, Hsieh et al. 2006) as well as natural mortality (Jørgensen and Fiksen 2010). This generally results in reduced productivity of fish stocks and higher vulnerability towards environmental changes and fluctuations. These dynamics feedbacks could be particularly problematic in view of potential threats through climatic changes (Perry et al. 2005, Brander 2007).

Reduced stock densities are another major factor to take into account in harvested populations. Density-dependence in larval and juvenile survival is commonly acknowledged as an essential part of population dynamics in fish (Rothschild 1986, Hilborn and Walters 1992, Houde 1994, Cowan et al. 2000). This is extensively implemented in most stock assessment models as density-dependent recruitment, i.e. a spawning stock-recruitment relationship, and long established in fisheries science (Ricker 1946, Beverton and Holt 1957). In comparison, density-dependent individual growth among recruited fishes has received little attention, despite evidence for its relevance in the regulation of fish stocks (Jenkins Jr et al. 1999, Lorenzen and Enberg 2002, Vincenzi et al. 2008) and its potential management implications (Helser and Brodziak 1998). In general, density-dependence results in increased growth potentials under low densities and may reinforce resilience of fish stocks towards fishing mortality.

There is increasing evidence that fishing may cause evolutionary changes (Law and Grey 1989, Conover and Munch 2002, Jørgensen et al. 2007, Law 2007, Hutchings and Fraser 2008, Allendorf and Hard 2009). Fishing mortality reduces the overall chance of survival and imposes a shift in the selection landscape of life-history traits. The mechanism and resulting adaptations have been documented in time-series analysis (Ricker 1981, Heino et al. 2002, Swain et al. 2007), experimental (Reznick and Ghalambor 2005, Conover et al. 2009, Conover and Baumann 2009) and modelling approaches (Ernande et al. 2004, Dunlop et al. 2009b). Today most commercial fish stocks are heavily exploited (Worm, et al. 2009, FAO 2011), fishing mortalities may therefore outnumber natural mortalities significantly (Mertz and Myers 1998) and cause rapid evolution (Darimont et al. 2009). Potential negative consequences for biomass and yield (Law and Grey 1989, Conover and Munch 2002), adult body size (Heino 1998, Enberg et al. 2011) or the recovery of depleted fish stock (Enberg et al. 2009) are contrasted by indications for heightened resilience towards fishing pressure (Enberg, et al. 2009, Enberg et al. 2010).

As ecosystems are subject to fluctuations and changes up to drastic regime shifts (Scheffer and Carpenter 2003, Mayer and Rietkerk 2004, Carpenter et al. 2008), fishing has been suggested as an indirect or direct cause for trophic shifts and ecological transitions (Jackson et al. 2001, Folke et al. 2004). In particular, predominant targeting of large predatory species and overfishing may cause cascading effects on the food web and result in alternative trophic regimes (Scheffer et al. 2005, Daskalov et al. 2007, Österblom et al. 2007, Casini et al. 2009). This corresponds with an observed decrease of mean trophic level of catches that indicates a dwindling of high-trophic level fisheries and increasing exploitation of lower trophic levels (Pauly, et al. 1998, Pauly and Palomares 2005, Essington et al. 2006, Branch, et al. 2010). It has been shown that this could create alternative stable states (Persson et al. 2007).

MANAGEMENT IMPLICATIONS

The complexity of marine ecosystems with multi-layered feedbacks to fishing reveals another major reason for failing fisheries. Correspondingly, the comprehensive understanding of the underlying biological system is a crucial component of successful fisheries management. But in reality most approaches are still rather simplistic. Traditionally, management efforts target on concepts like MSY (Larkin 1977) and preventing growth or recruitment overfishing (Beverton and Holt 1957, Sissenwine 1987, Myers et al. 1994). The corresponding biological reference points (Gabriel and Mace 1999) and size limits remain therefore predominant. However, the crude single-species perspective neglects evolutionary and plastic consequences as well as the ecosystem point of view.

The proportion of big individuals in a population could be one major parameter for improved sustainability (Berkeley, et al. 2004b, Birkeland and Dayton 2005). This idea is based upon the avoidance of recruitment overfishing, but links to concerns of growth overfishing too. The concept of growth overfishing dates back to Beverton and Holt (1957) who pointed out the relevance of age structure and the growth of corresponding cohorts. When individuals of a cohort are allowed to grow sufficiently, the resulting yield per recruit is optimized and a biologically efficient harvest is achieved. More recent studies add the additional dimension of maternal effects. There is evidence for higher larval survival of older female spawners (Berkeley et al. 2004a) with impacts on lifetime reproduction (O'Farrell and Botsford 2006). Here, considering individual growth and age-dependent effects can therefore not only maximize the harvested yield from a cohort, but increase recruitment and overall population stability (Murawski 2000, Anderson, et al. 2008). Thus, several threads of evidence suggest that taking into account age structure and individual size may be crucial parameters to determine optimal sustainable harvest (Tahvonen 2008, Diekert et al. 2010).

The potential impact of fishing-induced evolutionary changes is a similar management concern (Heino 1998, Ashley et al. 2003, Jørgensen, et al. 2007, Dunlop et al. 2009a). As fishing has the ability to affect the evolution of life-history traits, consequences for the biomass of fish stocks and their resilience towards environmental change are likely, ultimately derogating sustainable yields of fisheries. Because evolutionary changes may be difficult or even impossible to reverse (De Roos et al. 2006), a careful assessment of evolutionary impacts and their mitigation with evolutionary sensitive reference points is necessary (Hutchings 2009).

The ecosystem perspective of fisheries management has gained much attention recently (Pikitch et al. 2004, Garcia and Cochrane 2005). In spite of the fast dissemination of the term itself, including FAO guidelines and others, the concept remained rather vague. Generally, ecosystem-approaches to fisheries imply a holistic perspective and aim for by-catch mitigation, multi-species management, avoidance of ecosystem degradation or integrated approaches (Morishita 2008). Hence, single-species stock assessments and reference points need to be replaced by appropriate metrics and management goals (Brodziak and Link 2002, Hall and Mainprize 2004, Jennings 2005). However, scientific progress and partial implementations initiated a potential paradigm shift (Murawski 2007).

In general, the management instruments to address biological challenges are limited. Specific management questions may obscure that the underlying mechanisms are restricted to gear selectivity and – overall, spatial or temporal – reductions of fishing mortality. Because gear selectivity is imperfect and very limited in some fisheries, e.g.

purse-seining, fishing mortality becomes often the only biological lever of regulatory control. At the same time, overfishing is the key driver of unsustainable fisheries, stock collapse and evolutionary or ecological changes. Accordingly, lowered fishing pressure can be considered as straight-forward remedy, addressing all described problems to some degree. Two threads take this up in particular: Precautionary approach and marine protected areas (MPAs). The precautionary approach focuses on uncertainty directly, using risk-minimizing reference points to ensure long-term sustainability (Garcia 1996, Hilborn et al. 2001). Similarly, MPAs attempt to mitigate uncertainties, consolidate stock productivity and resilience and reduce ecosystem impacts with no-take zones (Sumaila et al. 2000, Grafton et al. 2005, Edgar et al. 2007).

BIOECONOMIC SYNTHESIS

"The current state of affairs, in which most professional economists ignore resource limitations and in which most ecologists maintain a proud disdain of economics, must give way to a science of renewable resource management based on sound principles of bioeconomics. "

Colin W. Clark, 1989

In view of the biological and socio-economic dynamics of fisheries, it becomes clear that only an interdisciplinary approach enables successful management. Bridging the gap, bioeconomics provide a crucial discipline to achieve the goal of sustainable, yet profitable fisheries and marine ecosystems (Hannesson 1993, Anderson and Seijo 2010, Clark 2010). In this respect, bioeconomic models are a useful tool to combine stock and fleet dynamics, balance biological precaution with economic efficiency, and generate comprehensive policy advice. However, implementing theory in practice has its pitfalls. In particular, adequate complexity in biological and economic parameters is crucial, or as in the canonical saying, models should be as simple as possible, but as sophisticated as necessary. Hence, to reach this goal while balancing the different perspectives summarizes the key challenge of bioeconomic models. It comes as no surprise that the previously described discipline biases, i.e. lack of biological or economic insight, respectively, is a key problem. To unify the different perspectives and explore potentially relevant mechanisms at the boundary of biology and economics is therefore crucial for successful bioeconomics. The research in the framework of this thesis was conducted in this spirit.

THESIS APPROACH

RESEARCH RATIONALE

To this point I discussed the biological and economic complexities of fisheries management, highlighting the need for integral bioeconomic research that combines both perspectives. This represents the root idea of this thesis: The basic quest throughout to bring more biology into economic questions and vice-versa, and thereby to improve utilization of fish stocks. In detail, the general research questions are:

- What is the value of body size?
- What is the economic impact of fishing-induced evolution?

The first question (**paper I**, **II**, **III**) ties in with the topic of growth overfishing and general importance of size-structure for fisheries. With a focus on size-dependent pricing, we emphasise the intrinsic economic value of body size directly. Thus, we provide a change of perspective with this previously understudied topic and underline the overall relevance of body size for fisheries. The second problem (**paper IV**) centres on potential evolutionary consequences of fishing by amending previous research with an economic assessment. This offers a first evaluation of possible evolutionary cost, and introduces at the same time an evolutionary dimension into fisheries economics.

THE VALUE OF SIZE

Individual growth has been long established as a key parameter in population dynamics of fish, and therefore also the prevention of growth overfishing for fisheries management (Beverton and Holt 1957). More recent studies corroborate the biological relevance of stock structure in context of survival and reproductive success further (Murawski, et al. 2001, Berkeley, et al. 2004b, Birkeland and Dayton 2005). Similarly, age and size structure are increasingly acknowledged as crucial factor for harvest optimization (Tahvonen 2008, 2009, Diekert, et al. 2010). However, another aspect has drawn little attention: The intrinsic economic value of body size, or size-dependent pricing.

It is common that ex-vessel prices for fish are weight-structured with increasing prices per weight unit for larger individuals. Simply speaking, big fish often fetch higher relative prices than smaller one. Correspondingly, an influence of size-dependent pricing on optimal harvest strategies has been suggested for a long time (Hilborn and Walters 1992). Yet just a few studies regarded this aspect to some extent (Gallagher et al. 2004, Holland et al. 2005, Tahvonen 2009). More frequently, size-dependent pricing was considered as a fixed component of fisheries without further analysis (e.g.Helser et al. 1996, De Leo and Gatto 2001, Katsukawa 2005). Therefore the goal was to fill this gap and demonstrate in two different approaches the influence of size-dependent pricing on optimal harvesting, as well as assess its prevalence in Norwegian fisheries. This involved quantifications in the framework of age-structured models (**paper I**) as well as an analytical approach (**paper II**) and a statistical analysis (**paper III**).

Paper I uses Atlantic herring (*Clupea harengus*) and Atlantic mackerel (*Scomber scombrus*) as example fisheries for the influence of size-dependent pricing on optimal fishing mortalities and resulting net present value (NPV). We use age-structured population models with size-dependent harvesting, and apply a price function based on a linear approximation of Norwegian price per weight class data (**paper III**) to allow for a smooth variation of the size-price relationship. This quantifies how size-dependent pricing may alter optimal fishing mortalities, and the resulting mean catch weight and NPV.

Paper II combines fishing-induced truncations of size structure with size-dependent pricing to study the consequences of size-dependent effects on sustainable rent and harvest paths. To permit an analytical approach we chose a lumped-biomass model, extended with relationships between fishing effort and mean individual size as well as size and price. This enables us to trace on a generic level how size-dependent effects change optimal harvest paths and sustainable rent.

Paper III contains an analysis of price data from Norwegian fisheries in respect to size dependence. This takes up the point of origin in paper I, but uses instead statistical methods to determine the overall prevalence and strength of size-dependent pricing in Norwegian fisheries. Because all previous work in this topic was mostly conceptual or restricted to mere case studies, **paper III** offers a first systematic approach. Moreover, it underlines the key assumption of **paper I** and **II** and therefore their conclusions.

Both modelling approaches conclude a reduction of optimal effort or fishing mortality under consideration of size structure and size-dependent pricing. This suggests that ignoring body size could lead to flawed strategies to achieve MEY, potentially causing rent dissipation and suboptimal performance of fisheries. From our results it follows that the impact of fishing on stock demographics and size-structured market prices should receive more attention in bioeconomic modelling and management policies.

THE COST OF EVOLUTION

As evidences for evolutionary consequences of fishing have been substantiated (e.g. Conover and Munch 2002, Law 2007, Hutchings and Fraser 2008, Allendorf and Hard 2009), the debate has shifted towards possible management implications of fishing-induced evolution (FIE) (Jørgensen, et al. 2007, Dunlop, et al. 2009a, Hutchings 2009). In summary, there is concern that FIE may impair stock biomass, stability and recovery potential, and therefore result in negative consequences for fisheries, particularly reduced yield and higher vulnerability to environmental change. However, existing work is mainly focused on biological consequences of FIE for fish stocks, their conclusiveness and adequate management response. On the other hand, there was little attention for the economic perspective, in spite of its crucial role for fisheries. Therefore, in **paper IV** we contribute an evaluation of potential economic impacts of FIE.

Our study contains a basic quantification of the economic impact FIE might have. In doing so, we extend traditional bioeconomic models not only with dynamics of a structured population, but with trait variation as well. Changeable traits have been rarely part of bioeconomic studies; therefore our approach includes general novelty in this context. In **paper IV** we compare an age-structured population dynamics model with evolutionary life-history to the same model with fixed traits. Maturation age acts as the only evolving trait in a key role and affects here growth, reproduction and survival directly, and is genetically inherited. Natural mortality and fishing are size-dependent and act as selective force. Additionally, the input parameters of fishing, size-selectivity and maximum fishing mortality, determine the catch and corresponding economic output. The parameterization is adjusted to the stock of Northeast Arctic cod (*Gadus morhua).*

The model shows a clear long-term impact of fishing-induced evolution on economic rent. However, the quantitative influence is generally rather insignificant. In particular, the differences between optimal fishing mortality and resulting MEY are low even under assumption of low discount rates. With higher discount rates, the effect of FIE becomes even negligible. Furthermore, in our model the fish stock demonstrates a higher resilience towards overfishing with FIE, pointing out potential advantages through evolutionary adaptation in specific situations. Our results predict also an evolutionary shift in size composition of stock and catch. This may be a concern in context of general fishing-induced changes in stock structure and consolidate related negative effects like reduced productivity and population stability on a genetic level. In economic terms, consequences of FIE could be enhanced when considering the value of size. Therefore a future extension of the model with size-dependent pricing is likely to predict more pronounced economic consequences.

The influence of discounting on the economic relevance of FIE underlines a problematic aspect with dynamic solutions to problems of optimal resource utilization. Traditionally, reasonable low discount rates, e.g. a social discount rate, demonstrated little influence on optimal harvest of fish stocks. However, precondition is a sufficient difference of magnitude between discount rate and intrinsic growth rate. Otherwise, optimal economic harvest can shift to levels higher than MSY or even suggest extinction (Clark 1973). Similarly, even high rates of human-induced evolutionary change are rather subtle and slow from a fisheries perspective. Therefore, as we have shown in **paper IV**, economic impacts of FIE may be very sensitive to choice of discount rate. This implies that FIE is for fisheries economics and in view of overall uncertainty rather irrelevant. Yet it appears ethically problematic to diminish the productivity of a fish stock for future generations, which raises the question if a conventional approach can do justice to such intergenerational problems (Lande et al. 1994, Weitzman 1998, Ainsworth and Sumaila 2005). This transcends to usage of natural resources and impact of environmental changes in general, and will require future research and debate. In particular, alternative concepts of discounting like e.g. decreasing discount rate over time await further exploration.

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